

# **Laser Damage Resistance of Photo-Thermo-Refractive Glass Bragg Gratings**

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## **ABSTRACT**

Thick Bragg gratings recorded in the volume of photo-thermo-refractive (PTR) glass have found wide application in high-power laser beam control. They have been successfully used for spectral beam combining, angular magnifying for beam scanning, selection of transverse and longitudinal modes in laser resonators etc. Laser damage was studied in PTR glass blanks and gratings fabricated under different conditions. No threshold reduction was found after grating recording in PTR glass. The laser damage threshold of a volume Bragg grating for a single mode 1 ns pulse at 1054 nm focused on inclusions was 7 J/cm<sup>2</sup>, while irradiation of inclusion-free sites resulted in surface damage at 20 J/cm<sup>2</sup>. N-on-1 laser damage tests 1 for 10 Hz repetition rate 1064 nm multimode 8 ns pulses focused to a 78 μm diameter spot have shown a 32 J/cm<sup>2</sup> threshold for a Pt-melted sample with detected inclusions, and a surface damage threshold greater than 42 J/cm<sup>2</sup> for a sample with no detected Pt-inclusions.

## **1. INTRODUCTION**

The technology of high efficiency volume Bragg gratings in a photo-thermo-refractive (PTR) glass was recently developed and used for high power laser beam control [1-3]. PTR diffractive optical elements have shown high robustness under harsh conditions of utilization at elevated temperatures and under high power laser irradiation. These elements were successfully used for spectral beam combining, angular magnifying for agile beam scanning, selection of transverse and longitudinal modes in different laser resonators, gradual beam attenuation, etc.

PTR glass is a multicomponent silicate glass with a wide bandgap. Such materials have no intrinsic absorption in the near IR spectral region and therefore their intrinsic laser damage threshold should be extremely high for both pulsed and CW irradiation [4]. This means that damage of this glass under CW irradiation should be caused by IR absorption of impurities (e.g. Fe<sup>2+</sup>) while laser-induced breakdown under pulsed irradiation should be caused by bulk inclusions or surface defects. Impurity absorption in the near IR is sufficiently low that PTR glass tolerates up to 100 kW/cm<sup>2</sup> of CW irradiation by a 1085 nm Yb-doped fiber laser focused to a spot diameter of 300 μm [1, 5]. Self-focusing of laser radiation in PTR glass occurs only at very high powers because of the low value of nonlinear refractive index, equal to that in fused silica [6]. Moreover, self-focusing is not a problem for most diffractive elements because of their small thickness. Therefore, the main cause of laser induced damage of PTR glass under real conditions of operation should be an explosion of different types of surface and bulk inclusions.

It was found in Ref. [7] that the surface laser damage threshold for PTR glass melted in a silica crucible was in the range of 10 J/cm<sup>2</sup> for a spot of 2 mm for a 1 ns pulse duration. This value is about 25% comparing to 40 J/cm<sup>2</sup> for the best samples of fused silica with very high surface quality and the same level as for standard optical glasses after standard optical finishing. These data enable the effective use of PTR glass and PTR diffractive elements in high power pulsed laser devices. However, no study has been done of the influence of glass technology and holographic element processing on laser-induced bulk damage of PTR glass and of Bragg gratings recorded in this glass.

Thus, the goal of this work was to study laser-induced damage of PTR glass fabricated with different glass melting technologies and hologram recording procedures and to determine the resistance of PTR Bragg gratings to high power pulsed laser radiation.

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## 2. EXPERIMENTAL

Application of optical materials in high power laser systems usually requires both high optical homogeneity and high laser damage threshold. The first requirement is usually satisfied by the use of Pt crucibles and stirrers in glass melting technology. However, this also results in the appearance of Pt inclusions, which decrease the laser damage threshold. Therefore we used two materials for glass melting equipment which were Pt and fused silica. Glass composition, melting procedure and conditions for annealing were the same for both technologies. Melting and stirring were performed in an electrical furnace at 1460°C. The PTR glass blanks were ground and polished with typical sizes 25×25 mm<sup>2</sup>. Thickness of the samples was from 1 to 5 mm. Only the samples with high optical homogeneity ( $\Delta n < 10^{-5}$ ) were used for laser experiments. Detection of Pt inclusions in the glass samples and selection of inclusions free samples were done by means of dark field optical microscopy.

UV illumination of the samples was produced by a 35 mW He-Cd laser at 325 nm for dosages ranging from 0.1 to 10 J/cm<sup>2</sup> in two regimes. The first was irradiation with a beam having a flat distribution of intensity. The second was irradiation with an interference pattern of the same beam produced by its splitting and combining. An interference pattern was produced to provide the spatial frequency and exposure necessary for formation of a volume Bragg grating with diffraction efficiency close to 100%. Thermal treatment of the exposed samples was done at 520°C for a few hours. Parameters of Bragg gratings were determined by measuring their angular and spectral selectivity at different wavelengths.

Laser-induced damage threshold measurement at 1054 nm was carried out in a setup including a single transverse and single longitudinal mode Nd-doped phosphate glass laser system combined with 110-X magnification dark-field optical microscopy for sample evaluation. The laser operated in a regime of single pulses of 1 ns duration. The beam was focused to a diameter of 0.7 mm in the sample plane. The testing was done with Pt defect targeting, i.e. on each tested site the largest point type bulk defect was centered relative to the laser beam and then irradiated. Regimes of irradiation were 1-on-1 (15-20 sites) and N-on-1 (ramp up, 4 sites). Laser-induced breakdown was detected by the appearance of new light scattering sites or by significant increase in size and light scattering of the targeted defect.

Laser-induced damage testing at 1064 nm was carried out by focusing the radiation of a multimode Nd:YAG laser to a spot of 78  $\mu\text{m}$  (FWe<sup>-2</sup>M). The laser operated in a periodically pulsed regime with a repetition rate of 10 Hz and pulse duration of 8 ns (FWHM). Maximum on-axis fluence was 43 J/cm<sup>2</sup>. The regime of irradiation was N-on-1 at fixed pulse energy up to 2000 pulses.

## 3. RESULTS AND DISCUSSION

Evaluation of the studied samples by means of dark field microscopy has shown that glasses melted in silica crucibles did not have bulk inclusions that could be detected with the used experimental setup while glasses melted in the Pt crucible contained bright particles with typical sizes of a few microns and less. The concentration of such inclusions depended on parameters of the melting process and typically varied from several particles per cubic centimeter to several per cubic millimeter. This feature of Pt-melted glass samples allowed focusing laser radiation to inclusions or to inclusion-free sites and selecting samples with no inclusions at all.

Laser-induced damage thresholds measured with 1 ns pulses at 1054 nm are shown in Table 1. In all cases when no inclusion was detected in the focal spot, laser induced damage took place on the surface of the sample. The values of

Table 1. Laser-induced breakdown thresholds (J/cm<sup>2</sup>) for PTR samples at 1054 nm, 1 ns pulses, 700  $\mu\text{m}$  spot diameter.

Glass	Crucible	Treatment	Damage origin	Damage threshold, J/cm <sup>2</sup>	
				1-on-1	N-on-1
PTR	Pt	Unexposed	Volume inclusions	5.3±0.5	2.9±0.6
PTR	Pt	Uniform Exp/Dev	Volume inclusions	8.0±0.6	5.8±1.4
PTR	Silica	Unexposed	Surface defects	30±4	
PTR	Silica	Uniform Exp/Dev	Surface defects	10.5±1.5	13.5±3
PTR	Pt	Exp/Dev Bragg grating	Volume inclusions	6.9±0.9	5.0±1.2
PTR	Pt	Exp/Dev Bragg grating	Surface defects	20±2	
Corning 7940		Pitch polishing	Surface defects	38±2	

the surface damage thresholds for different samples have shown strong variation depending on the treatment history and quality of finishing. The surface damage threshold for the original glass reached  $30 \text{ J/cm}^2$  which is about 25% lower than for fused silica after pitch polishing used for the Omega facility. The decreased threshold for exposed and developed samples probably resulted from surface defects produced during thermal development. It was found that partial surface crystallization occurred on the PTR glass sample surfaces after thermal development. Boundaries between microcrystals and glass surface could have a high concentration of surface defects. This is why re-polishing of the Pt-melted sample with a Bragg grating resulted in higher damage threshold compared to an exposed silica-melted sample which was not subjected to full-scale re-polishing. It is important to note that alignment of the beam to the grating's Bragg angle did not result in lowering of damage threshold.

The damage threshold for the largest inclusions in unexposed PTR glass samples is about 4 times less than that for the glass matrix (Table 1). This damage shows significant accumulation effect resulting in decreasing of the threshold to  $3 \text{ J/cm}^2$  after multiple irradiation of the same site. It is an interesting finding that for samples containing Pt inclusions, the process of UV exposure followed by thermal development leads to an increase of laser-induced damage thresholds in both uniformly exposed samples and samples with volume gratings. This means that additional absorbing inclusions (if any) that could be produced in the process of thermal development have no impact on laser-induced damage thresholds. It is well known that one of the species produced in PTR glass at elevated temperatures are colloidal particles of metallic silver (see e.g. Ref. [8]). These particles are responsible for the yellowish coloration of developed PTR glasses. However, the size of the particles is probably too small to be effectively heated by  $1054 \text{ nm}$ ,  $1 \text{ ns}$  laser pulses. Moreover, one can see that damage thresholds of developed glass blanks and volume gratings are higher than those in unexposed glass. This suggests that thermal development of PTR glass at rather low temperatures in the range of  $500^\circ\text{C}$  can result in some type of structural modification of Pt particles produced in the melting process.

The results of testing with the  $10 \text{ Hz}$  repetition rate laser are shown in Fig. 1. One can see that no significant statistical scattering of threshold values exists for samples with no Pt inclusions and the laser-induced damage threshold is above  $40 \text{ J/cm}^2$ . In all cases, laser-induced damage occurred on the surface of the samples. This suggests that no other inclusions with damage threshold lower than that of the surface defects exist in Pt-melt PTR glass. The threshold value is about twice as high as that for  $1 \text{ ns}$  pulses. This threshold ratio approximately corresponds to the familiar square root dependence of threshold on pulse duration.

The results of testing of the samples with Pt inclusions show strong scattering of threshold values with broad overlapping of damaging and undamaging fluence regions. This may be attributed to the statistical distribution of sizes of Pt inclusions and their positions relative to the laser beam. The lowest damage threshold is about  $30 \text{ J/cm}^2$ . This value is about 10 times higher than that for N-on-1,  $1 \text{ ns}$  testing and indicates significant deviation from square root threshold/pulse-length dependence. This might be related to the small, about  $80 \mu\text{m}$ , spot size for  $8 \text{ ns}$  laser pulses, which is much smaller than the average distance between inclusions. Testing of a grating recorded in Pt-melt PTR glass has shown a surface damage threshold of about  $20 \text{ J/cm}^2$ . This result means that no additional decreasing of damage threshold occurs in the hologram writing process while the quality of finishing is the

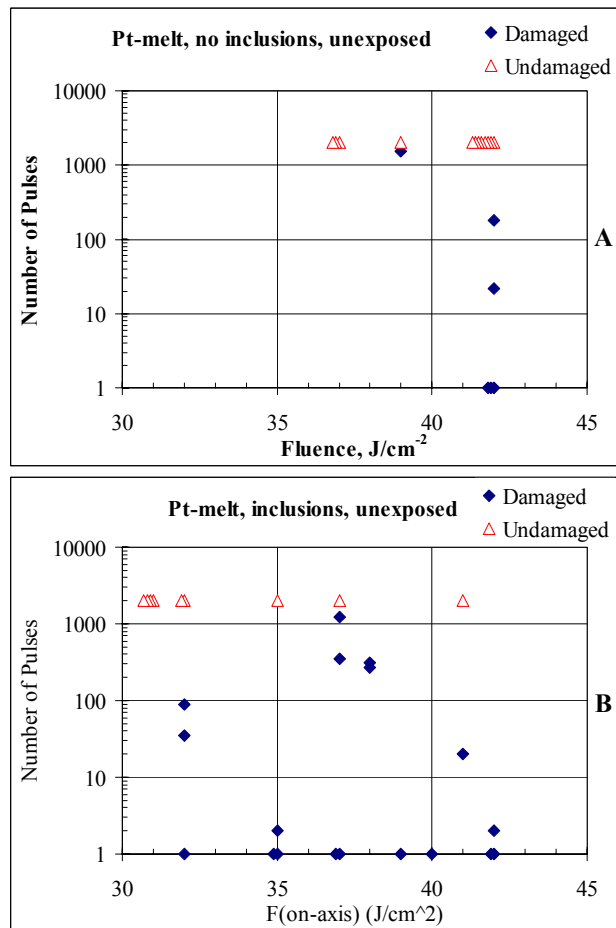


Fig. 1. Laser-induced breakdown thresholds for  $1064 \text{ nm}$   $8 \text{ ns}$  pulses N-on-1 at fixed energy. A – sample with no inclusions, B – sample with inclusions.

main factor which finally determines laser damage resistance of PTR diffractive elements.

#### 4. CONCLUSIONS

Inclusion-free samples produced from PTR glass melted in a platinum crucible show surface damage thresholds of 20 and 40 J/cm<sup>2</sup> for 1 and 8 ns pulses, respectively, for both original samples and samples with volume Bragg gratings. Samples with inclusions show N-on-1 bulk damage thresholds of 3 and 30 J/cm<sup>2</sup> for 1 and 8 ns pulses, respectively. Some threshold increase was found after UV exposure and thermal development of the samples. No threshold decrease occurs if the incident angle of testing irradiation is set to the Bragg angle of the volume grating. Diffractive optical elements made from PTR glass can be used in high power pulsed laser systems.

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